

Mass modelling of Abell 2634: avoiding the interloper bias

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Abstract Using an example of the Abell 2634 galaxy cluster we discuss the effect of contamination of kinematic data by interlopers and its impact on mass modelling. The cluster data reveal rich substructure along the line of sight. We demonstrate that it is necessary to apply a few independent methods of interloper removal in order to obtain a reliable sample of cluster members. We present results of three such methods which are commonly used in the literature and have been recently extensively tested on simulated data. Only two of them lead to consistent and reliable samples of cluster galaxies. For both of them we provide parameters of the best-fitting NFW density profile by fitting an isotropic solution of the Jeans equation to the velocity dispersion profiles.

1 The Abell 2634 galaxy cluster

Abell 2634 is a nearby galaxy cluster at redshift $z = 0.0314$. At present there are 230 galaxies with measured spectroscopic redshift available within the aperture of 3 Mpc around the cluster centre. The data, extracted from the NASA/IPAC Extragalactic Database (NED), are presented in the upper row of Figure 1 in the form of the so-called velocity diagram, in which velocities v of galaxies in the rest frame of the cluster are plotted against projected distances R from the cluster centre.

The cluster has a relatively regular image in X-rays and possesses a Bright Central Galaxy whose position coincides with the global maximum of the surface distribution of the X-ray emitting gas. This means that the object is expected to be nearly in dynamical equilibrium and all methods of mass inference involving assumptions of relaxation can be reliably applied. However, the distribution of galaxies in the velocity diagram is not as regular as one could expect from this picture. It reveals two groups of interlopers (background and foreground galaxies seen due to projection effects) probably due to the presence of two structures gravitationally unbound to the cluster but positioned along the line of sight. This kind of data contamination may lead to significant systematic errors in mass estimates. Reliable inferences concerning the mass distribution thus require careful selection of cluster members.

2 Removal of interlopers

No method exists which would allow us to discriminate between the cluster members and interlopers with certainty. Any galaxy observed in the direction of a cluster can belong

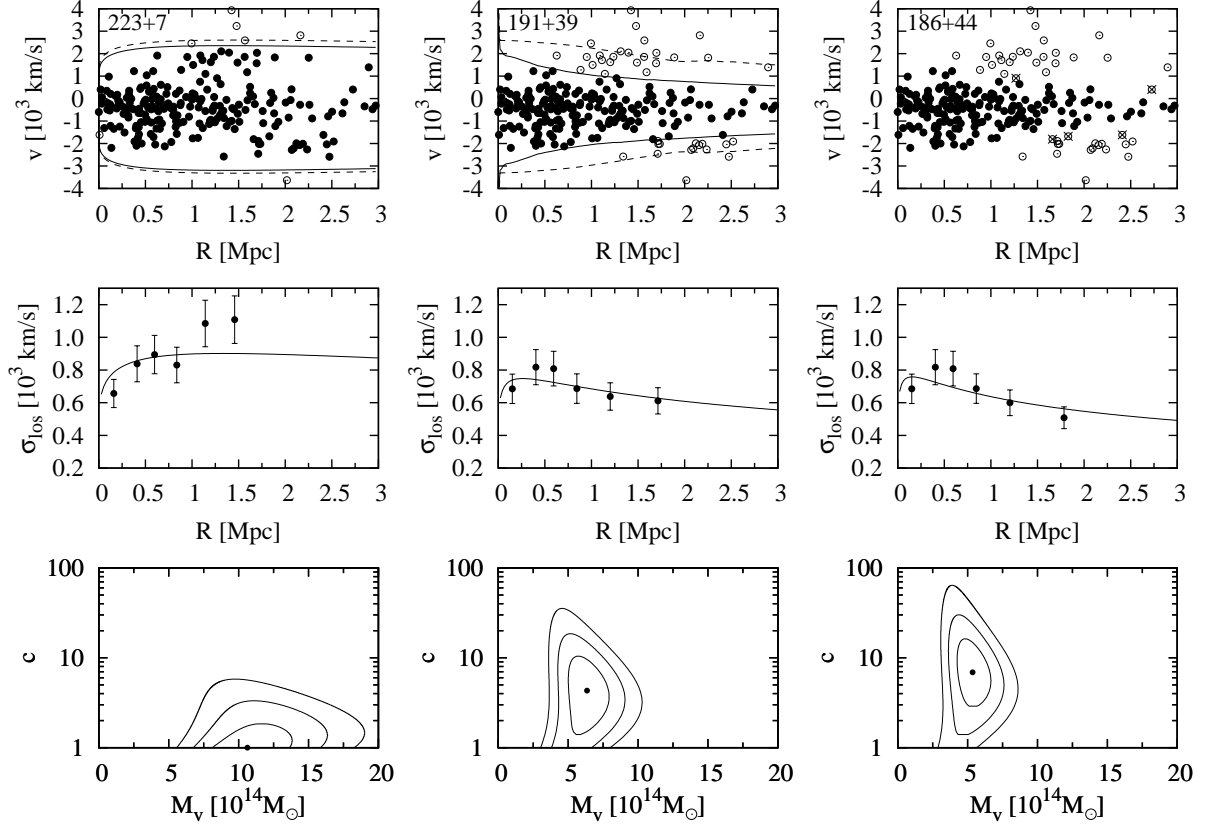


Figure 1: Results of interloper removal applied to the kinematic data for A2634. Columns from the left to the right correspond to the $3\sigma_{\text{los}}(R)$, $v_{\text{max}}(R)$ and M_P/M_{VT} methods. Open and filled symbols in the velocity diagrams (upper row) stand for the identified interlopers and cluster members respectively (the numbers of points of both groups are given in the upper left corners). Dashed and solid lines plotted there indicate velocity envelopes from the first and the last iteration of a given method. The middle row shows the dispersion profiles corresponding to the different samples of cluster galaxies and the best-fitting solution of the Jeans equation for isotropic orbits (solid lines). Results of the fitting in terms of 1σ , 2σ and 3σ confidence regions in the $M_v - c$ parameter plane are shown in the bottom row.

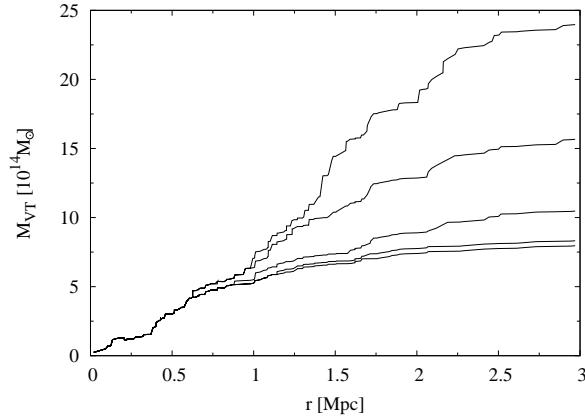


Figure 2: Profiles of the virial mass estimator obtained in the subsequent iterations of the $v_{\max}(R)$ method.

to this system as well as be seen in the sample only due to projection effects. However, the probability of observing a cluster galaxy is not the same for all objects: galaxies with small velocities in the rest frame of the cluster belong physically to the system with more probability than high-velocity galaxies. Therefore the key idea to handle the problem of interloper identification is to introduce an envelope $\pm v_{\text{lim}}(R)$ around the systemic velocity of the cluster, which separates the area of the velocity diagram preferentially occupied by cluster members. Then the galaxies with velocities exceeding the boundary line $\pm v_{\text{lim}}(R)$ are suspected to be interlopers and should be rejected from the sample.

As shown by Wojtak et al. (2007), for the best methods the rate of identification of gravitationally unbound galaxies reaches the efficiency of 60-70% (for the initial cut-off in velocity of about $3-4\sigma_{\text{los}}$), which is close to the maximum value available. On the other hand, the final data sample still possesses some residual contamination of background galaxies. Moreover, some cluster members are lost due to unavoidable uncertainty of each method. However, fractions of both types of galaxies, i.e. lost cluster members and remaining interlopers, are of the order of 2-3% and have negligible impact on the final estimate of the mass profile. In the following we present three typical methods of interloper removal, which were found to work well on simulated as well as real data (for details see Łokas et al. 2006, Wojtak et al. 2007 and Wojtak & Łokas 2007), and apply them to the data for A2634.

In the first, rather natural approach (hereafter $3\sigma_{\text{los}}(R)$ method) velocity envelope is determined by

$$v_{\text{lim}}(R) = 3\sigma_{\text{los}}(R), \quad (1)$$

where $\sigma_{\text{los}}(R)$ is the line-of-sight velocity dispersion profile given by the projected solution of the Jeans equation for isotropic orbits (the anisotropy parameter $\beta = 0$) fitted to the data (see Łokas et al. 2001 and Łokas et al. 2006 for details). This formula is a generalization of the original concept by Yahil & Vidal (1977), who proposed to eliminate

interlopers via $3\sigma_{\text{los}}$ clipping where σ_{los} was the total velocity dispersion of the cluster. The interlopers are removed iteratively in a sequence of dispersion fitting and rejection of outliers. The results of this method applied to the data of A2634 are shown in the upper left panel of Figure 1. The method identified and rejected only 7 interlopers marked with open symbols (the 7th rejected galaxy in the very centre is probably a member).

The next approach (labelled hereafter $v_{\text{max}}(R)$) was originally proposed by den Hartog & Katgert (1996). Considering boundary conditions for the velocity field in virialized objects, they showed that the velocity envelope could be well approximated by the maximum of the projection along the line of sight of the circular velocity vector \mathbf{v}_{cir} and the infall velocity vector $\mathbf{v}_{\text{inf}} = \sqrt{2}\mathbf{v}_{\text{cir}}$, namely:

$$v_{\text{lim}}(R) = \max_R \{v_{\text{cir}} \sin \theta, v_{\text{inf}} \cos \theta\}, \quad (2)$$

where θ is the angle between the position vector with respect to the cluster centre and the line of sight. The mass which is required to calculate the circular velocity $v_{\text{cir}} = [GM(r)/r]^{1/2}$, is approximated by the mass estimator based on virial theorem $M_{VT}(R)$

$$M(r) \approx M_{VT}(R = r) = \frac{3\pi N}{2G} \frac{\sum_i (v_i - \langle v \rangle)^2}{\sum_{i>j} 1/R_{i,j}}, \quad (3)$$

where $R_{i,j}$ is the projected distance between the i -th and the j -th galaxy and N is the number of galaxies in the sample. Inserting this formula into equation (2) one can evaluate the $v_{\text{lim}}(R)$ profile numerically. Again, interlopers are removed from the data iteratively until all galaxies are enclosed within the velocity envelope.

The velocity diagram in the upper middle panel of Figure 1 shows the $\pm v_{\text{lim}}(R)$ profiles of the first (dashed line) and final (solid line) iteration of this method applied to the data for A2634. The final sample of cluster members (191 galaxies) is indicated with filled circles, whereas interlopers (39 galaxies) with open symbols. Mass profiles obtained in subsequent iterations of the method are plotted in Figure 2 with the highest line for the first iteration and the lowest one for the last. One can see how succeeding steps of the procedure eliminate mass overestimation caused by the contamination of the galaxy sample by gravitationally unbound objects.

The third method which proves rather efficient in removing the interlopers (labelled hereafter M_P/M_{VT}), is based on the analysis of the relative bias of two mass estimators, the virial mass estimator M_{VT} defined by (3) and the so-called projected mass estimator M_P given by

$$M_P = \frac{32}{\pi G N} \sum_i (v_i - \langle v \rangle)^2 R_i. \quad (4)$$

As shown by Perea et al. (1990), the interlopers are the main source of bias of both mass estimators and one can use the jackknife statistics to eliminate them from the cluster sample. The moment of convergence could be found by investigating M_P/M_{VT} and dM/dn profiles as functions of the number of removed galaxies n_{rem} . As demonstrated by Wojtak et al. (2007), the maximum number of removed interlopers is signified by a characteristic

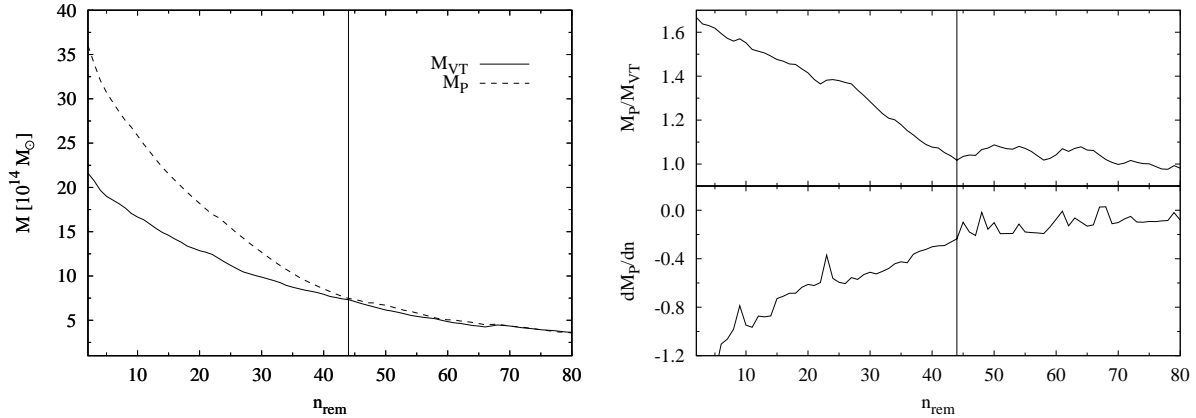


Figure 3: The mass estimators M_{VT} and M_P , the ratio M_P/M_{VT} and dM_P/dn as functions of the number n_{rem} of galaxies removed from the sample by the jackknife technique. In each panel the vertical solid line indicates the moment of convergence $n_{\text{rem}} = 44$, when the number of eliminated interlopers is probably largest.

knee-like point between the rapidly varying part of the M_P/M_{VT} profile and its plateau extension. Figure 3 shows the detection of this point in the case of A2634. The $n_{\text{rem}} = 44$ interlopers removed in this procedure are indicated with open circles in the velocity diagram shown in the upper right panel of Figure 1. The method identifies 5 more interlopers (marked with crosses) than the $v_{\text{max}}(R)$ approach.

3 Conclusions

A2634 is an example of a cluster with kinematic sample significantly contaminated by interlopers. As discussed by Wojtak & Łokas (2007), for such objects the $3\sigma_{\text{los}}(R)$ method converges too early and leaves in the sample a non-negligible number of gravitationally unbound galaxies. On the other hand, the $v_{\text{max}}(R)$ and M_P/M_{VT} methods lead to much more consistent and reliable samples of cluster members. This fact manifests itself also in terms of mass modelling. The middle row of Figure 1 shows the dispersion profiles of the corresponding samples of cluster members. The bottom panels demonstrate results of fitting an isotropic solution of the Jeans equation with NFW density profile (Navarro, Frenk & White 1997) involving two free parameters, the virial mass M_v and concentration c .

As expected, the result for the sample obtained with the $3\sigma_{\text{los}}(R)$ method still reveals features characteristic for interloper bias, i.e. the inferred density profile is flat ($c = 1$) and the mass is significantly overestimated with respect to the results obtained for samples from other interloper removal schemes. On the other hand, confidence contours obtained for the other two samples agree well with each other. This indicates that these two samples of cluster members are reliable. The best-fitting parameters for the $v_{\text{max}}(R)$ method are:

$M_v = 6.4_{-1.4}^{+1.5} \times 10^{14} M_\odot$ and $c = 4.3_{-2.9}^{+6.1}$ (1σ errors) while for the M_P/M_{VT} method we find $M_v = 5.4_{-1.2}^{+1.3} \times 10^{14} M_\odot$ and $c = 6.9_{-4.0}^{+9.3}$. Note that when the assumption of isotropy is relaxed and kurtosis is added to the analysis to constrain all three parameters, M_v , c and anisotropy β , the result is not very different, i.e. still isotropic orbits are preferred by the data (see Wojtak & Lokas 2007).

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